

# A Simple Beam Line for the MuCool Test Area

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## Abstract

This note describes a simple beam line to transport  $H^-$  beam from the end of the Fermilab 400 MeV Linac to the MuCool Test Area (MTA). The design uses existing dipoles and quadrupoles and other equipment now available at Fermilab. Deflection of single 15 Hz beam pulses from the Linac to the MTA is accomplished using pulsed magnets that are essentially Main Injector trim dipoles with thinner laminations. The beam size is kept small to control beam losses and allow the use of existing surplus or spare equipment. An upgrade of the beam line to illuminate larger objects at high intensity is described.

## Introduction

The MuCool Test facility will be used to test liquid hydrogen absorbers for muon beam cooling for a Neutrino Factory or Muon Collider as well as to test high gradient RF cavity structures and cavities that are cryogenically-cooled or superconducting. At first this equipment will be tested without beam. Later, after the beam dump and shielding berm are finished, the equipment will be tested with beam.

To test liquid hydrogen absorbers, the MuCool experimenters would ultimately like a beam of  $H^-$  or protons with 400 MeV kinetic energy, 50 mA peak current, and 50 microsecond pulse length at 15 Hz with variable beam size (from 1 to 30 cm at the device under test). Of course this beam must be delivered with tolerable beam losses. These demanding requirements, particularly the high intensity and the desired variability in beam size make the optics, operation, and shielding of such a facility particularly challenging and costly.

However, a beam with limited integrated intensity and small transverse size will satisfy the initial needs of some of the experimenters, such as tests of pressurized RF cavities by Muons, Inc. and the irradiation of detector components with small intensity beams or short bursts of high intensity pulses for MuCool. Accordingly, this note presents a simple design of a conventional beam line that can be built in the near future based on

components that are now available as spare parts or left over from previous projects. This design can be upgraded to provide the full capabilities required for complete testing of large devices with intense beam. The simple beam line design, components, cost, and operating conditions, as well as an upgrade for testing objects of large transverse dimensions, are discussed below.

### **Beam Line Design**

The design presented here is based on using eight of the fifteen spare quadrupoles from the Linac to Booster transfer line and six dipoles from the decommissioned Electron Cooling Ring.

#### **Extraction**

The beam will be directed toward the MuCool Test Area using two pulsed dipole magnets with the first located after the last Linac accelerating module and just before the Q74 quadrupole and the second just downstream of the chopper. At 400 MeV, this pair of magnets will produce a horizontal bend of 5 degrees. The magnets will pulse fast enough to allow only one of the Linac's 15 Hz beam pulses to be selected by an appropriate T-clock event, just as the NTF operates now.

There are at present two options for the pulsed magnet and power system to be used for extraction from the Linac. The first option is to use a pair of new magnets based on a Main Injector trim magnet design with a corresponding power supply designed by Dan Wolff. A second option would be to build a new copy of the 32-degree NTF magnet, which could be powered by a spare Transrex power supply. Here we describe only the first option, which seems more desirable considering long-range maintenance.

#### **Pulsed Extraction Magnet Design**

To achieve the required 5-degree bend while keeping the magnetic field under 0.65 T to avoid stripping the H<sup>-</sup> ions, we use two identical magnets, one on either side of the chopper. The magnets are built using laminations from IDH dipoles (Main Injector horizontal trims) with a hollow conductor coil for lowered inductance and improved cooling. The first magnet bends the beam 2.5° (44 mr). The second magnet is centered 1.75 m downstream of the first, on the other side of the chopper where the beam is separated from the straight Linac beam by 7.6 cm. A 5 cm (2 inch) diameter vacuum pipe carries both beams through the magnet, with the straight beam passing between the coils and the extracted beam passing through the center of the magnet.

Standard 0.635 mm laminations of transformer steel are suitable for pulsed operation. The IDH die exists and is in good shape. Figure 1 shows the lamination profile and DC field distribution. The coils are three layers of seven turns each on each pole. The conductor is 10.4 mm square copper with a 5.8 mm cooling water passage. The coils are wrapped in fiberglass tape and vacuum impregnated. Each magnet needs to contribute 0.14 T-m to the bend. Scaling from the IDH measurements, the dipoles will need to run

at 385 A. The water flow is sufficient at this current to allow DC operation, so pulsed mode operation will be stable.

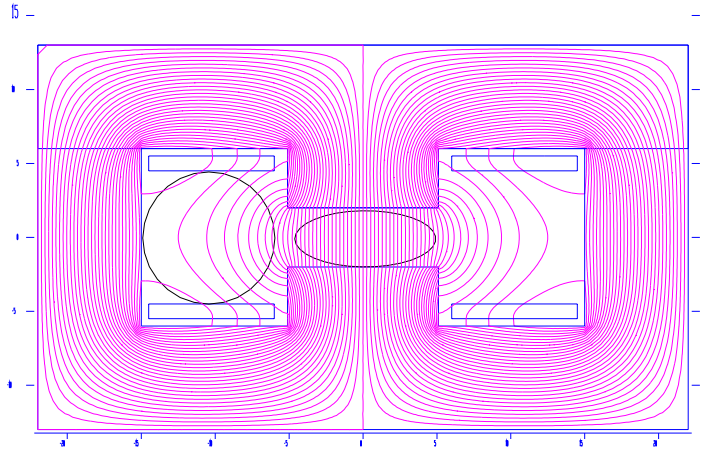


Figure 1. IDH dipole (Main Injector horizontal trim) profile showing field calculation. In the case of the second, downstream pulsed magnet, the straight-ahead Linac beam pipe passes through the magnet between the coils as shown by the circle in the figure.

### **Wolff Pulsed Power Supply**

The estimated cost of a pulser for the magnets described above is based on two 1 meter magnets operating at 0.14T with a 3"x3" aperture. This corresponds to 90 joules of stored energy. Another 40% has been added to account for fringing and end effects (total=126 joules). Depending on the eddy-current losses, the estimate ranges from \$8k to \$18k for component costs, where the lower value would correspond to using a ceramic beam pipe. The estimates do not include any accelerator controls modules, the cost of cables (controls, load, and AC), or the cost of cable installation (electricians).

### **Linac Modifications**

In order to place the first pulsed magnet upstream of the chopper, the prototype bunch length detector (BLD) can be removed (gaining 9 inches) and the quadrupole and wire scanner can be reconfigured to be closer together, as they are in other areas of the Linac, (gaining another 3 inches). These components are shown in figure 2. The development of the BLD can continue using the other two BLDs that are installed elsewhere.

The round cover on the downstream end of the Chopper shown in figure 3 has to be modified to accommodate the second new, pulsed dipole. The beam pipe to the Booster

and the one to the MTA separate at the cover and pass through the downstream pulsed-dipole as shown in figure 1.

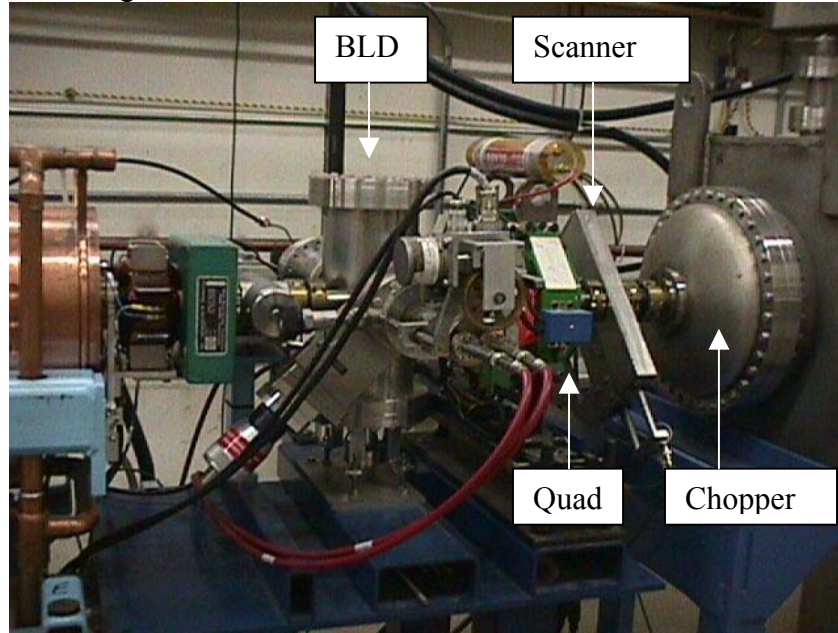


Figure 2. Proposed upstream pulsed-magnet location. The Bunch Length Detector can be removed, and the Quadrupole and Wire Scanner can be moved closer together nearer to the chopper to free up twelve inches for the pulsed magnet.



Figure 3. Area downstream of the Chopper. The Wire Scanner and the Transformer can be moved downstream. The downstream cover on the Chopper will have to be modified to allow the insertion of the downstream pulsed magnet with the two beam pipes as indicated in figure 1

## Linac to MTA Extraction Area

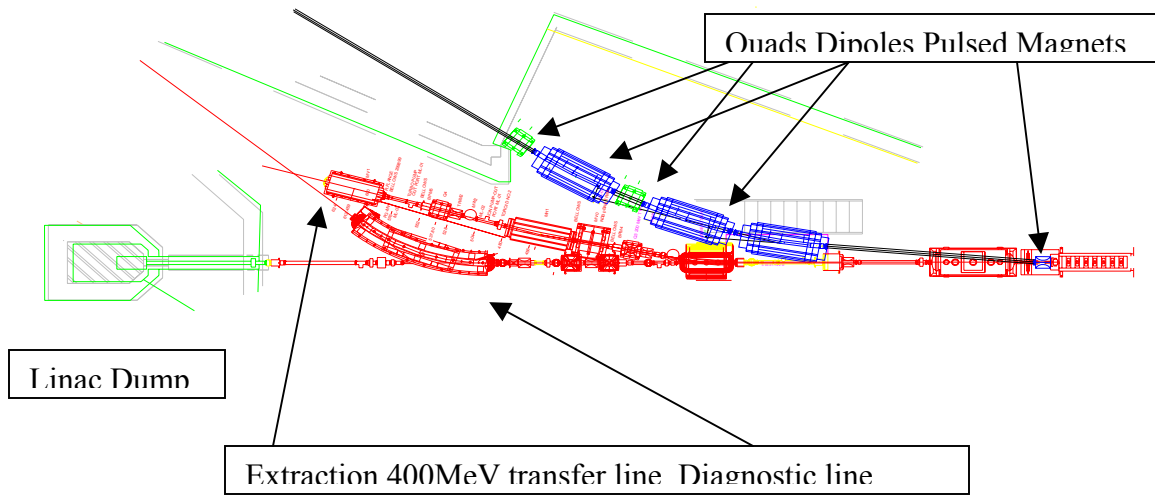


Figure 4. Extraction Area

## Linac to MTA Beam Line

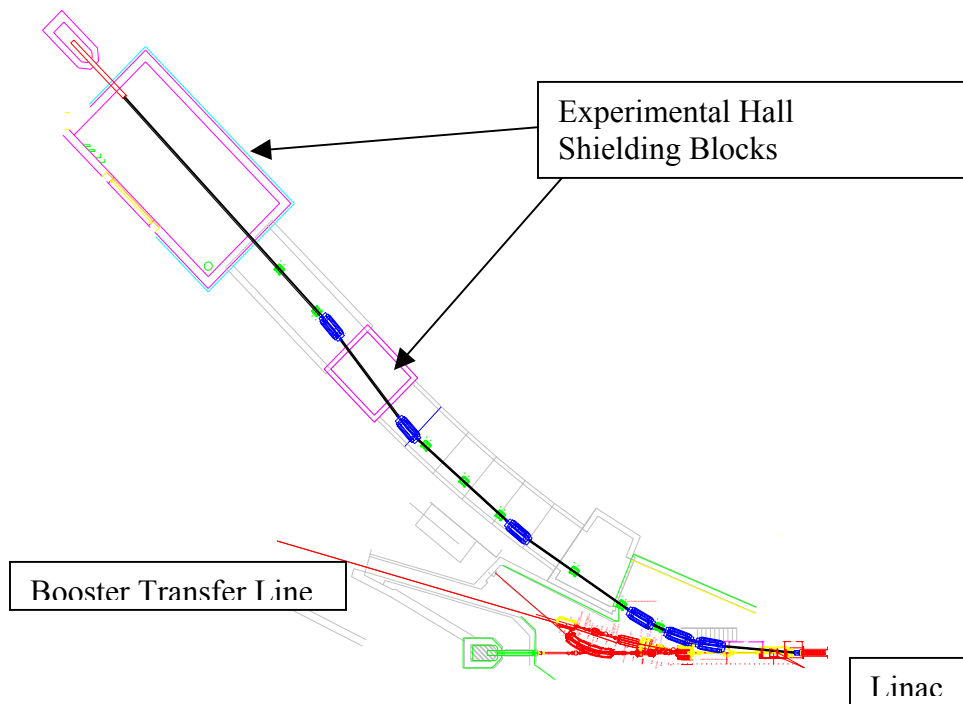


Figure 5. MTA Beam Line.

Five bending magnets each bend the beam 9 degrees to the right and the sixth bending magnet bends the beam to the left 9 degrees, as shown in figure 5.

## Beam Transport Simulations

A TRACE 3-D beam transport simulation starting from the upstream end of the last Linac module is shown in figure 6. In this simulation the last dipole magnet and two quadrupoles are just after the Linac shielding wall such that the beam drifts through the experimental enclosure to the dump area. Input beam parameters in the figure correspond to measured values.

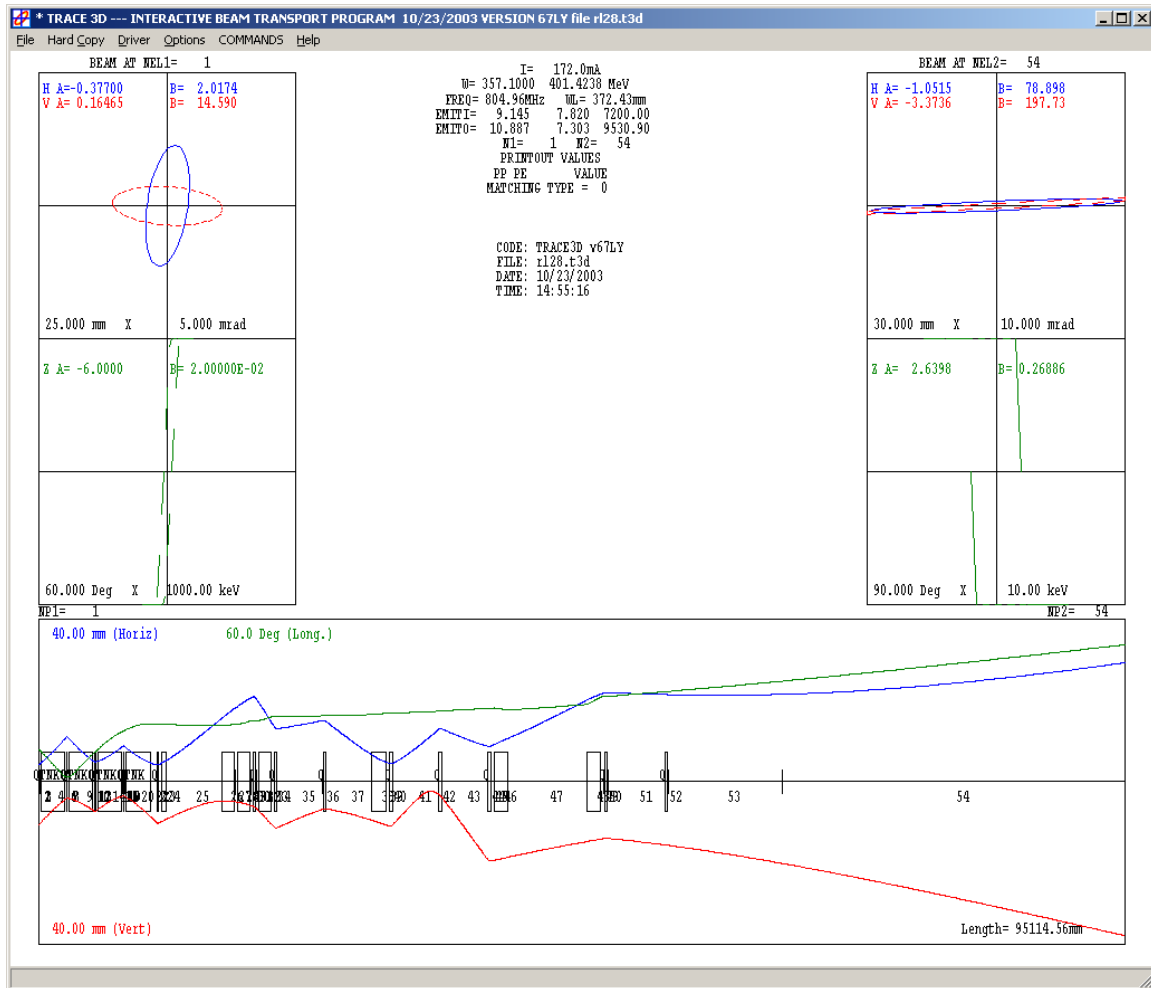


Figure 5. TRACE 3-D simulation of the proposed beam line. The blue line is the horizontal and the red line is the vertical beam envelope. The green line is the bunch length in degrees of 805 MHz RF wavelength.

The total emittance of the equivalent uniform beam (the beam followed by TRACE 3-D) in each phase plane is five times the rms emittance in that plane, and the displayed beam envelopes are  $\sqrt{5}$ -times their respective rms values. Real beams have ill-defined

boundaries and, in general, one can expect a few percent ( $<10\%$ ) of the particles in a real beam to be outside the boundaries displayed by TRACE 3-D.

### **Real Estate and Utilities**

Electrical power for the magnets is available from the L3 1500kVA transformer in the lower Linac gallery. This transformer powered the 200 MHz RF stations that were removed when the Linac was upgraded to 400 MeV. In the Linac lower gallery there is space for the power supplies. One Transrex power supply will power the pulsed magnet and two more will power the two groups of three dipoles. The same gallery will also house the rack with the six power supplies (similar to PowerTen) needed for the quadrupoles. Power cables will enter the Linac enclosure using existing linac penetrations. The two quadrupoles and any other magnets in the Experimental enclosure will be powered using power supplies housed in the Cryo Building and will get power from the MuCool transformer.

### **Operating Conditions**

We envision several operating scenarios. First of all we assume that beam switching from the Linac is clean and that we lose less than 1% of the beam within the Linac enclosure. The H<sup>-</sup> beam is transported to the last bending magnet in the Linac enclosure where a proton beam can be generated using a stripping foil. The magnet body and the enclosure shielding-wall will absorb unstripped H atoms. The number of particles that will be delivered to the area will be controlled with three independent parameters: repetition rate, pulse width, and Linac current. The present Linac can deliver a maximum of 50 mA of H<sup>-</sup> for up to 50 $\mu$ s, at up to a 15 Hz rate.

Any of these three parameters can be smaller by a factor ten or more. The maximum beam intensity may be limited by the installed shielding. The allowed beam loss within the Linac enclosure will be controlled by a loss monitor (sc200) in the Linac gallery and a monitor on the top of the berm. These monitors will inhibit beam on a pulse-to-pulse basis.

The line is designed under the assumption that loss can occur only in an accident condition. The pulsed magnet power supply and the power supply for the first three horizontal bending magnets will be the two critical devices that prevent beam from entering the MuCool experimental area.

### **An Upgrade for Objects with Large Transverse Dimensions**

It is difficult to duplicate the qualities of muon beams to be found in future muon colliders or neutrino factories with the Fermilab Linac beam. Besides the fact that muons have different energy loss behavior than protons, it is difficult to make the pulses short and intense enough to mimic beams in these future machines. As examples, a beam pulse for a collider may have  $10^{13}$  muons in a few nanoseconds while a neutrino factory beam

may have  $10^{13}$  muons in a few microseconds. However, with a maximum current of 50 mA, it takes 32 microseconds to accumulate  $10^{13}$  particles with the Linac.

Thus, any experiment to test equipment for these uses must have a plan to simulate the beam in some believable way. For large aperture liquid hydrogen energy absorbers it has been assumed that the MuCool test area should have the ability to illuminate an absorber with a wide beam by means of a system of large-aperture quadrupoles. However, we note that the narrow beam that is the subject of this paper can be scanned across the absorber with a system of programmed dipoles to illuminate the absorber with considerable flexibility and reduced cost. In this case the dipoles would be arranged to form a three or four-bump in each transverse plane such that the beam could be directed to the beam dump after passing through the absorber.

With such a scanned beam, the instantaneous rates (particles/s/mm<sup>2</sup>) in each region of the absorber can be made to be more like those of cooling applications to be simulated.

### **Components and Costs**

All magnets except the pulsed dipoles used for extraction (and the programmed dipoles that could be used in an MTA upgrade to the beamline for scanning large test devices) exist and are available. The spare Linac quads should be ready, though the six dipoles will probably need to be refurbished at some additional cost. Trim magnet specifications should be made considering the availability of existing magnets and supplies.

Eight quadrupoles can be powered by 30V/320Amp or 50V/60Amp power supplies that are standard power supplies used in the AD. The six dipoles from the Electron Cooling Ring experiment can be powered in groups of three using two Transrex power supplies from decommissioned Fixed Target Lines. As discussed above, the pulsed extraction magnets can be powered by an available Transrex or by a special supply that would be built according to contemporary AD standards.

The vacuum system, including pipes, bellows, pumps, power supplies, and pressure readouts, can be constructed from materials from decommissioned beamlines. Diagnostics, readouts, and control system components may also be available, although compatibility requirements with the accelerator controls may dictate some additional expenses to minimize total operation and construction costs.

In all cases, the detailed design of the beamline should be made with available components to minimize costs and to facilitate a timely construction schedule.

### **Acknowledgment**

We thank Dan Wolff for his help in estimating the power supply parameters for the pulsed magnets.